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NOL HYPERSONIC TUNNEL NO. 4 RESULTS IV:
HIGH SUPPLY TEMPERATURE MEASUREMENT AND CONTROL

8 October 1952

U. S. NAVAL ORDNANCE LABORATORY
WHITE OAK, MARYLAND

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NOL HYPERSONIC TUNNEL NO. 4 RESULTS IV:

HIGH SUPPLY TEMPERATURE MEASUREMENT AND CONTROL

Prepared by:

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ABSTRACT: Results of investigations on measurement and control of high supply temperatures of the continuous NOL 12 x 12 cm Hypersonic Tunnel No. 4 are presented. The operation of electric heaters (total power of about 200 KW) is discussed and it is found that after a preheating period without tunnel operation, it takes about 5 minutes while the tunnel runs to raise the inlet air temperature to 500°C. If once attained, the supply temperature can be kept automatically constant for any length of time within ± 0.5°C. The upper T_0 limit of the equipment has not yet been determined but will be above 500°C. The development of subsonic total temperature probes is discussed. The means by which a uniform temperature distribution across the nozzle inlet was achieved is described. Also exterior wall temperatures are given as function of time. For safe operation equipment temperatures limit the duration of the blow to several hours. Finally a description of heaters and their performance is included as appendix.

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This is the fourth NAVORD Report on an investigation carried out in the U. S. Naval Ordnance Laboratory Hypersonic Tunnel No. 4. This program was jointly sponsored by the U. S. Naval Bureau of Ordnance and the U. S. Air Force Flight Research Laboratory. The tests described in this report lay the groundwork for future precision measurements on the characteristics of hypersonic flow in the hypersonic wind tunnel.

The author wishes to acknowledge the cooperation of Messrs. H. Staab and R. Garren. Messrs. H. Staab and C. White were responsible for the design of the 40 KW and 72 KW heaters. The appendix was written jointly by H. Staab and the author.

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Aeroballistic Research Department
By direction

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NOL HYPERSONIC TUNNEL NO. 4 RESULTS IV:

HIGH SUPPLY TEMPERATURE MEASUREMENT AND CONTROL

I. INTRODUCTION

1. If wind tunnels are to be operated at Mach numbers above 5, the supply air must be preheated to avoid air condensation (references a and b). Furthermore, the supply pressure must be raised to high values to obtain reasonably high test section pressures and densities and to stay out of the slip-flow regime. These two factors introduce high pressure and high temperature techniques to hypersonic wind-tunnel design. Since these problems, in particular the high temperature operation, are generally new to supersonic wind-tunnel workers, the experience gained at NOL on this subject to date will be related.

2. The NOL 12 x 12 cm continuous Hypersonic Tunnel No. 4 (reference b) presently operates at supply pressures up to 30 atmospheres and at supply temperatures from room temperature up to above 500°C. These conditions permit tunnel operation in a Mach number range of from 5 to 10 (reference c). The work leading to a constant and uniform supply of hot air will be discussed here.

3. Three groups of problems are connected with this subject:
(a) First it is desired to obtain any temperature in the given range at various supply pressures. This supply temperature is to be reached quickly and asymptotically without damage to the source of heat. If once attained, it is to be held constant for any length of time. This group of problems concerns the air heaters, their design, operation, and control.
(b) The second group of problems is connected with the measurement of the supply air temperature, development of suitable instrumentation, and achievement of temperature uniformity in a reference cross-section ahead of the nozzle inlet.
(c) Finally the effect of high temperature on the wind-tunnel structure, operational safety, and effect on instrumentation must be studied.

II. OPERATION AND CONTROL OF ELECTRIC HEATERS

4. The over-all arrangement of the hypersonic tunnel and its auxiliary components is shown in Fig. 1. Presently three electric heaters are installed in the supply system with load capacities of 80, 72, and 40 KW.

5. The 80 KW unit is a custom-built Westinghouse two-range heater. Details on its design, circuit, and performance are given in the appendix. This heater (called I) is positioned directly above

the tunnel in a settling tank where air at low velocity (approximately 1 ft/sec) and high pressure (p_o) passes directly over the hot nichrome elements. The amount of heat to be fed into the air is controlled by a bare-wire thermocouple located in the neck below the tank. The readings of this thermocouple actuate a Leeds and Northrup[1] recording controller. The electric program controlling mechanism added to this instrument permits approach to a desired temperature asymptotically in a pre-set time interval and maintains the temperature at the control point within pre-set limits.

6. However, for the initial heating period, i.e. starting with the entire system at room temperature, and for a desired $T_o > 200°C$, the demanded temperature cannot be approached automatically without danger of overheating the nichrome elements. (Permissible element temperature for continuous operation 900°C; see appendix.) This possible overheating is due to poor heat transfer from the heater elements to the low speed air. It was found practical to follow a routine by which the demand temperature approaches the final supply temperature in a number of manually set steps and to decrease the heating rate with increase of temperature. For each intermediate temperature the heater is left on automatic control until a reasonably safe ratio of air to element temperature is reached. This procedure is illustrated in Fig. 2.

7. To shorten the initial heating period during a run at elevated temperature, the system (Fig. 1) may be preheated and the air discharged into the atmosphere via the by-pass line. The residual heat stored in the walls, pipes, etc. after such preheating is sufficient to reduce to a few minutes the time necessary to reach high supply temperatures during the actual test. Once attained this temperature is then kept constant within ± 0.5°C for any length of time by the action of the proportional heat controller (Leeds and Northrup, 10769-G M.E.C. unit).

8. Heater II, the 40 KW unit, designed and built at NOL is installed in the supply line ahead of the Westinghouse heater. It is operated without automatic control, and serves mainly (a) to reduce the load of heater I, and (b) to shorten the initial heating period. Its construction using industrial Calrod elements, and a general description of performance is given in the appendix. The air entering this heater at the bottom usually has a temperature of 0°C or below due to the Joule-Thomson temperature drop caused by nearly adiabatic throttling in the pressure regulator. Heater II raises this temperature to approximately 250° to 300°C. Most of the heat is lost in the heating of ducts, the 5000 lbs pressure tank, etc.

9. The combined capacities of heater I and II limit the air discharge through the nozzle to 1.2 lbs per sec if a temperature of 310°C is to be maintained in a continuous run. This limit corresponds to a tunnel operation at a Mach number of about 7.5 and a supply

pressure of about 20 atmospheres. (Of course higher temperatures can be achieved at higher Mach numbers with correspondingly lower mass discharges at equal or higher pressure.)

10. To overcome this power limitation, a 72 KW unit, (heater III), built like heater II, has recently been added to the system ahead of heater II. Its design and general description is also included in the appendix. Like the 40 KW unit, heater III has no automatic control. For most operating conditions either one or both of these heaters are kept in operation, depending on the temperature level required. The automatic control provided for heater I assures a constant supply temperature and its proper value. To prevent overheating of the Calrod elements in the auxiliary heaters, their surface temperature is also continuously recorded. By increasing the mass flow over the elements using the by-pass line, while tunnel conditions remain constant, the Calrod surface temperature can be kept below the recommended maximum temperature of 800°C. Fig. 3 gives the element temperature of heater I and the air temperatures after heater III as well as of heater I as function of the time for one typical operating condition. Comparing this figure with Fig. 2 shows that the addition of the 72 KW unit not only makes it possible to pre-set a program for the automatic controller but also cuts the initial heating time down from 30 minutes to about 18 minutes. (No preheating through by-pass preceded this test.)

11. If heater I and III are operated simultaneously, their combined capacity is sufficient to maintain a supply temperature of 330°C for any length of time for a mass discharge of 1.6 lbs per sec (Mach number of 7.6 and supply pressure of 28 atmospheres). Correspondingly higher temperatures and/or pressures can again be used for higher Mach numbers.

III. DEVELOPMENT OF SUPPLY TEMPERATURE THERMOCOUPLES

12. For aerodynamic measurements, the true stagnation temperature (T_o) in the settling tank must be known. Deviations of temperature indicated by a thermocouple from true total temperature are to be expected if the measurements are made in a moving air stream, and if the walls and external supports of the thermocouple are at temperatures different from the air temperature. The amount of the deviation is a function of the air velocity and the efficiency of the probe to register, without losses, the temperature of a surrounding air sample.

13. The location of the measuring probe - either in the neck between heater I and the tunnel inlet, or below the filter screen* - is

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*a stainless steel wire mesh screen (mesh size .15 to .30 mm) inserted above the nozzle inlet (Fig. 1) to retain extraneous particles. Such particles originate at several places in the supply. They are powdered activated alumina from the dryer, ceramic from heater insulation, metallic particles (welding), metallic oxydes, etc.

of no importance since effects due to flow velocity are negligible in either case. The flow velocity in both cross-sections is of the order of 10^{-2} of the sound velocity and at this speed only about 10^{-6} of the thermal energy of the gas at rest is converted into kinetic energy and would have to be recovered by the probe. Deviations of the measured temperature from actual T_0, however, may be due to conduction losses along the thermocouple wire and support, and due to radiation from the heater elements and hot walls upstream of the probe as well as radiation from the junction towards cooler walls.

14. To minimize these errors, the usual approach has been followed (reference d). To reduce conduction losses, the wire supports have been insulated from the walls of the probe and a certain length of the wire behind the junction is exposed to the same temperature as the junction itself. The thermocouple is surrounded by vented shields to reduce radiation errors and to promote the establishing of temperature equilibrium around the junction.

15. To determine the amount of shielding adequate to measure T_0 within ± 1 percent of its true value or better, various shielded probes were tested under a variety of operating conditions. Fig. 4 and 5 show a photograph and the design of this probe. The 20-gauge iron-constantan thermocouple is supported by ceramic two-hole insulators inside a stainless steel protection tube. The projection of the junction out of the support is approximately 5/16 inch, assumed to be a sufficient length to minimize conduction errors along the wires. The high pressure seal to the tunnel outside is made either of compressed talcum powder (Conax design[2]), or by sealing the wires into the end of the gland cavity with 'Technical B Copper Cement'[3]. The vented radiation shields are made of stainless steel with a chromium plating on the inside and outside which remains bright up to temperatures of about 450°C. End plugs to block out "sight" of walls were used in some tests with the double-shielded and triple-shielded probes.

16. The readings are taken with Brown temperature recorders (model 153X11P-X-28 A1)[4]. The recorder accuracy is 0.2 percent of full scale of the recorder. To determine the correction for any specific temperature, the thermocouples connected by the needed lengths of lead-wire to the recorders were calibrated against thermometric standards. This procedure was selected since it combines all corrections* into one curve. The fix points selected are: ice - 0°C, boiling water - 100°C, freezing points of tin - 231.9°C, lead - 327.3°C, zinc - 419.5°C (certified samples of tin, lead, and zinc were obtained from the NBS). The comparison of the readings of the bare-wire, single-shielded and double-shielded probes (without end plugs), under identical external conditions, in the temperature range from room temperature to about 400°C is shown in Fig. 6 and 7. A comparison of the results obtained with further shielding (triple

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*Due to non-uniformity of the thermocouple wire, various lengths and non-uniformity of lead-wire, and recorder accuracy.

shield, and end plugs) is given in Fig. 8. These data were obtained with the probes in cross-flow. A comparison of the readings from a double-shielded probe in cross-flow with one directed towards the flow is given in Fig. 9. The differences are within the experimental accuracy of the test. As a consequence of the results shown in Fig. 6 through 9, double-shielded thermocouples without end plugs, mounted in cross-flow, are considered sufficiently accurate for measuring the supply air temperature and its distribution within ± 1 percent. It should be mentioned here, that the disadvantage of using an insufficiently shielded probe - bare-wire or single shield - is not only its generally lower reading but the fa t that the readings are unstable, sometimes fluctuating by as much as 10° to 20°C.

17. As will be seen later, T_o measurements made in the neck between heater I and the nozzle inlet cannot be relied upon because of further heat loss of the supply air. The T_o test-readings must be made in the duct between filter screen and nozzle throat. Due to the limited space available below this screen (cross-sectional area 1.5 x 4.75 in.), the probe size was reduced to 1/8 in. O.D. One of the probes is shown in Fig. 10. Its basic design (Fig. 11) is the same as used for the larger probes. The thermocouple is of 30-gauge calibrated iron-constantan wire, insulated in two-hole ceramic tubes with a stainless steel protection tube around it. Three series of vent holes are bored into the two radiation shields surrounding the junction; the shields are thermally insulated from the metal protection tube by 'Technical B Copper Cement'. Comparison of the large and small probes shows that both give identical readings within ± .5°C in the temperature range from room temperature to above 400°C.

IV. ACHIEVEMENT OF UNIFORM TEMPERATURE DISTRIBUTION IN NOZZLE INLET

18. The temperature distribution at various operating conditions has been investigated in two cross-sections ahead of the nozzle inlet; in the neck between heater I and the fast acting valve, and below the filter screen, see Fig. 1. The results are shown in Fig. 12 and 13. These distributions are a function of time, with the uniform center portion flattening out as the wall temperature increases. The following table illustrates the rate of approach to practically steady state temperature distributions in the two cross-sections investigated. The time is counted after the set T_o is attained in the center of the nozzle inlet

Time (min)	Rate of wall temperature increase (°C/min) below filter screen	above neck
0	1.1	1.3
10	0.9	1.0
20	0.8	0.85
30	0.7	0.8
40	0.6	0.75
50	0.5	0.7
60	0.45	0.6
70	0.4	0.5
90	0.2	0.35

19. Fig. 12 and 13 show the supply temperature distribution to be non-uniform. This poor T_o distribution can be related to the design of the supply system. For instance, the dilation of the region of maximum temperature toward the North (Fig. 12) is found due to air deflection from the radiation shield (Fig. 1) installed below heater I. The offset of the isothermes towards East correlates with the disturbance in the temperature field introduced by the by-pass line entering at this side. This effect is still more emphasized if air is discharged through the by-pass. The same non-uniformity of T_o is found below the filter screen.

20. To improve the T_o distribution below the filter screen, a baffle system followed by a honeycomb, both made of steel, were installed. The baffle system achieves a mixing of the heated air and the honeycomb, a block of 3/4 inch thickness and a ratio of total to open area of 6:1, directs the flow parallel to the tunnel axis. The heat conduction in this block tends to further equalize the temperature. Originally, honeycomb and baffles were directly attached to the steel walls of the duct. A typical temperature distribution achieved with this arrangement is shown in Fig. 14. The plateau of homogeneous temperature now covers practically the entire free opening of the duct.

21. A water cooling system, installed in the top of the casing of the test section (Fig. 1) to maintain the nozzle throat opening at a constant value by preventing dilation of the working section top once more offset the temperature distribution. Insulation of the baffle system and honeycomb from the cooled duct portion by 1/4 inch thick asbestos lining and installation of an asbestos frame for the filter screen restored a homogeneous temperature distribution. Design details of the duct are shown in Fig. 15.

22. Temperature distributions obtained at 200°, 300°, and 400°C are given in Fig. 16 through 18. Irregularities in the isothermes still present are due to small leaks to the outside from the high pressure (up to 30 atm) in the settling tank. The temperature measured in the center of the neck is a linear function of that measured in the center of the duct below the screen, a fact that makes it possible to determine T_o in the neck with a single large thermocouple. (T_o filter screen)/(T_o neck) = 0.93.

23. Assuming density and velocity constant across the inlet, average values of T_o may be obtained by integration from plots such as those in Fig. 16 through 18. The average T_o is lower than the temperature measured in the center of the duct. This correction appears to be linear with temperature and ranges from -2°C at 100°C up to -10°C at 450°C.

24. Finally, the stagnation temperature has been measured with specially developed supersonic total temperature probes across the flow in the test section at Mach numbers ranging from 5 to 8. It is found that this total temperature is about constant outside the

boundary layer on a traverse from one nozzle wall to the other. It therefore appears that the uniform supply temperature distribution yields, as expected, a uniform test section total temperature distribution.

V. EFFECT OF HEATING ON WIND TUNNEL STRUCTURE

25. The high supply temperatures are in due course transmitted to all components of the wind tunnel structure by heat conduction in the metal and heat transfer by forced convection from the air flow. Though the components are designed for continuous operation at high supply pressure and temperature, local "hot spots" may occur due to unforeseeable peculiarities of design and flow.

26. Surveys of the temperature assumed by the exterior walls of many parts of the equipment were made with a Pyrocon[5] portable thermocouple and indicator (temperature range 0° to 800°F). Readings are effected with this instrument by firmly touching the surface to be tested with the thermocouple head. Thermocouples were permanently installed externally at the 5 hottest points of the tunnel and their temperatures are recorded during each run. Typical temperature histories of these 5 control points and 6 other sample locations along the tunnel walls are shown in Fig. 19 and 20.

27. The outside temperatures of Fig. 19 and 20 are indicative for the ranges of temperature to which materials and techniques used for gasketing, lubricants, window mounting, probe and model supports, etc. are exposed to. Relatively low temperatures are measured on top of the heater tank because of the radiation shielding inside the tank. 540°C aluminum paint[6] is used on the inside metal surface, and a 4 inch thick insulation surrounds the heater elements (Fig. 1). Since there is a low rate of heat transfer to the test section walls, due to low test section densities, the temperatures remain low enough to permit the use of glass windows (1 inch thick selected commercial plate glass) for flow observations in tests of 30 minutes to 2 hours' duration, depending upon M, p_o , and T_o . However, the higher temperatures obtained at stations of higher rates of heat transfer, especially at the diffuser section, cause convective air currents outside the tunnel over the test section windows necessitating the complete enclosure of the optical path for schlieren observations. Also glass windows cannot be exposed for more than very short periods of time to the flow without cracking. Fused quartz windows are presently being investigated for high temperature operation.

VI. SUMMARY

Supply temperatures ranging from room temperature to above 500°C are needed to operate wind tunnels in the range $5 \leq M \leq 10$.

The heating conditions are met for continuous operation of the NOL 12 x 12 cm Hypersonic Tunnel No. 4 by electric heaters of a total power of about 200 KW.

It takes about 20 minutes to raise the wind tunnel supply temperature to a constant high value in the above range.

Once attained, T_0 can be maintained for hours of operation within $\pm$ 0.5°C by automatic control.

Double-shielded and vented thermocouples give an accurate indication of the actual wind tunnel supply temperature.

A uniform temperature distribution in the inlet area of the hypersonic nozzle is achieved by an empirically determined insulated baffle system and honeycomb built into the inlet duct. For supply temperature between 100 to 450°C measured in the center of this inlet, the average temperature obtained for the entire area from an integrated temperature survey is only 2 to 10°C lower. This uniformity recurs in a constant stagnation temperature measured in the test section outside the boundary layer.

Continuous tunnel operation is limited to several hours due to the severely increasing temperatures of all components that are not cooled. Safety considerations make a continuous recording of heating element, exterior wall and other component temperatures imperative.

VII. REFERENCES

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(c) Wegener, P., High Temperature Operation of Hypersonic Tunnels, Second Bureau of Ordnance Symposium on Aeroballistics, 13-15 May 1952, Pasadena, California

(d) Mullikin, H. F., Gas-Temperature Measurement and the High-Velocity Thermocouple, Temperature Symposium of the American Institute of Physics (1939) (Temperature, Its Measurement and Control in Science and Industry, American Institute of Physics, Reinold Publishing Co., New York (1941))

(e) Galloway, V. H., NOL, unpublished data

APPENDIX I

Electric Heaters

A. Heater I

The heater is enclosed in a 4-inch thick insulated chamber (Fig. 21a) located in the high pressure settling tank of the wind-tunnel supply section (Fig. 1). The supply air enters this chamber through a gap of approximately 3 inches between the side wall case and a radiation shield cover. It then circulates downward past the heating elements into the nozzle.

Terminals designed and constructed at NOL (Fig. 22) are used to transmit the power from a 440 volt 3 phase power supply into the pressure tank. The heater unit itself is composed of 60 elements arranged in horizontal groups of 5 and off-set vertically (Fig. 21b). The elements are connected in 3 groups of 20 elements each. Each group is connected to a separate power terminal. Each element is a nichrome[7] strip 0.70 by 3/8 inch wide, wound on edge into helical form with an outside diameter of 2 1/8 inches. The coil is supported over the 13 inch span by a nichrome strip beam covered with molded ceramic insulators. Each of the 60 beams are again insulated from the nickel steel frame by ceramic parts.

B. Controls for Heater I

Heater I can be operated either manually by using the "low range" and "high range" breaker-switches at the bottom of panel II, Fig. 25, or automatically by a Leeds and Northrup controlling pyrometer of the proportional type (No. 10769 - G M.E.C. unit). This unit also provides automatic program control for the initial heating period. In the "low range," the top and bottom banks of the heater elements are connected in series with the middle bank parallel to them. For supply air temperatures requiring operation of the "low range" only, the Leeds and Northrup controller operates an on-off breaker on one power line. The switch is actuated by the sensing mechanism that compares the temperature pre-set as desired with the actual air temperature in the nozzle inlet. The rate of approach to the desired temperature, the desired temperature tolerance and the permissible over-shoot can be controlled by the programming device. In the "high range," and if the temperature is at the pre-set control point, the three element banks are switched from a delta connection to a connection where the middle and bottom banks are in series and the top one parallel to them in contrast to the complete on-off operation provided in the "low range" control.

For operational safety of the heater elements, a Wheelco Limitrol[8] is used to disconnect the three-pole power breaker on panel II whenever the over-temperature thermocouple indicates a value higher than the selected operation temperature. This safety thermocouple (chromel - alumel) is located in the center of the middle bank; its junction is protected from the cold side walls by a ceramic shield. Since this thermocouple does not read actual element temperatures, the maximum cut-off setting of the Limitrol has been determined prior to final installation of the heater. At atmospheric pressure, the elements were operated at the maximum permissible temperature of about 900°C which was measured by an optical pyrometer. Simultaneously the value registered by the safety thermocouple was noted. For an actual element temperature of 900°C (optical pyrometer reading) this thermocouple indicated only 740°C. The cut-off setting of the Limitrol, however, was selected at a lower temperature of 700°C because tests performed to determine the number of extraneous condensation nuclei present in the tunnel supply air (reference e) showed that a transient cloud of nuclei is given off if the element temperature is raised above 700°C.

C. Heaters II and III

Heater II is a 40 KW, 230 volt single phase line heater composed of 10 "Calrod"[9] tubular heaters with an over-all length of 86 inches and rated at 4 KW each. The tubular heaters are bundled around a stainless steel core tube made porous with vent holes. This tube is encased in a series of stainless steel outer jackets. The entire unit is suspended by straps from the top end in the vertical portion of the 4 inch extra-strong supply line piping, as shown in Fig. 1. The heater is connected so that 5 branches are in parallel, each branch being two heaters in series.

The 72 KW heater is a further development of heater II. A cutaway view is included in Fig. 1. The identical Calrod heaters have been used; however, the number has been increased to 18. Six are located around the periphery of an inner-core tube and twelve are located on the outer circumference of the jacket of the inner six heaters. This outer ring of 12 heaters is also enclosed in a sheet stainless steel jacket.

This heater differs from heater II in that the connections are delta 230 volt 3 phase with 6 Calrods per bank, and that air flow cools the outer pipe by concentric reversed flow. The reversed flow is accomplished by allowing the entering air to pass along the inside of the outer pipe flowing from the bottom toward the top and being reversed at the top into the middle concentric ring of 12 heaters to flow downward; at the bottom it is again reversed to flow upward through the inner ring of six heaters after which it emerges at the top of this heater unit.

Control of both heaters is manual. Control of operational safety of the Calrod elements (maximum operating temperature is about 800°C) is provided by Wheelco Limitrols in the same manner as used with heater I.

D. Performance

Performance of the heaters has been checked by recording element temperatures, air temperature increase in the heaters, and exterior wall temperatures as functions of time, supply air temperature and mass discharge (Fig. 24, 25, and 19). Since temporary, local overheating of the elements is not avoidable due to non-uniformities of the air flow or due to line voltage fluctuations, element metal may vaporize and condense on the insulation. This is checked by periodic measurements of the resistance-to-ground of the elements both with power on and off. Inspection of the sediments gathered at the filter screen after a run also enables one to judge aberrations that occurred in heater operation.

APPENDIX II

List of Manufacturers

1. Leeds and Northrup Company
   Philadelphia 44, Pennsylvania

2. Conax Sales Company, Inc.
   Kenmore 17, New York

3. W. V-B Ames Company
   Fremont, Ohio

4. Brown Instrument Company
   Philadelphia 44, Pennsylvania

5. Illinois Testing Laboratory, Inc.
   Chicago 10, Illinois

6. Sherwin-Williams Company
   Cleveland, Ohio

7. Driver-Harris Company
   Harrison, New Jersey

8. Wheelco-Instruments Company
   Chicago 7, Illinois

9. General Electric Company
   Schenectady, New York

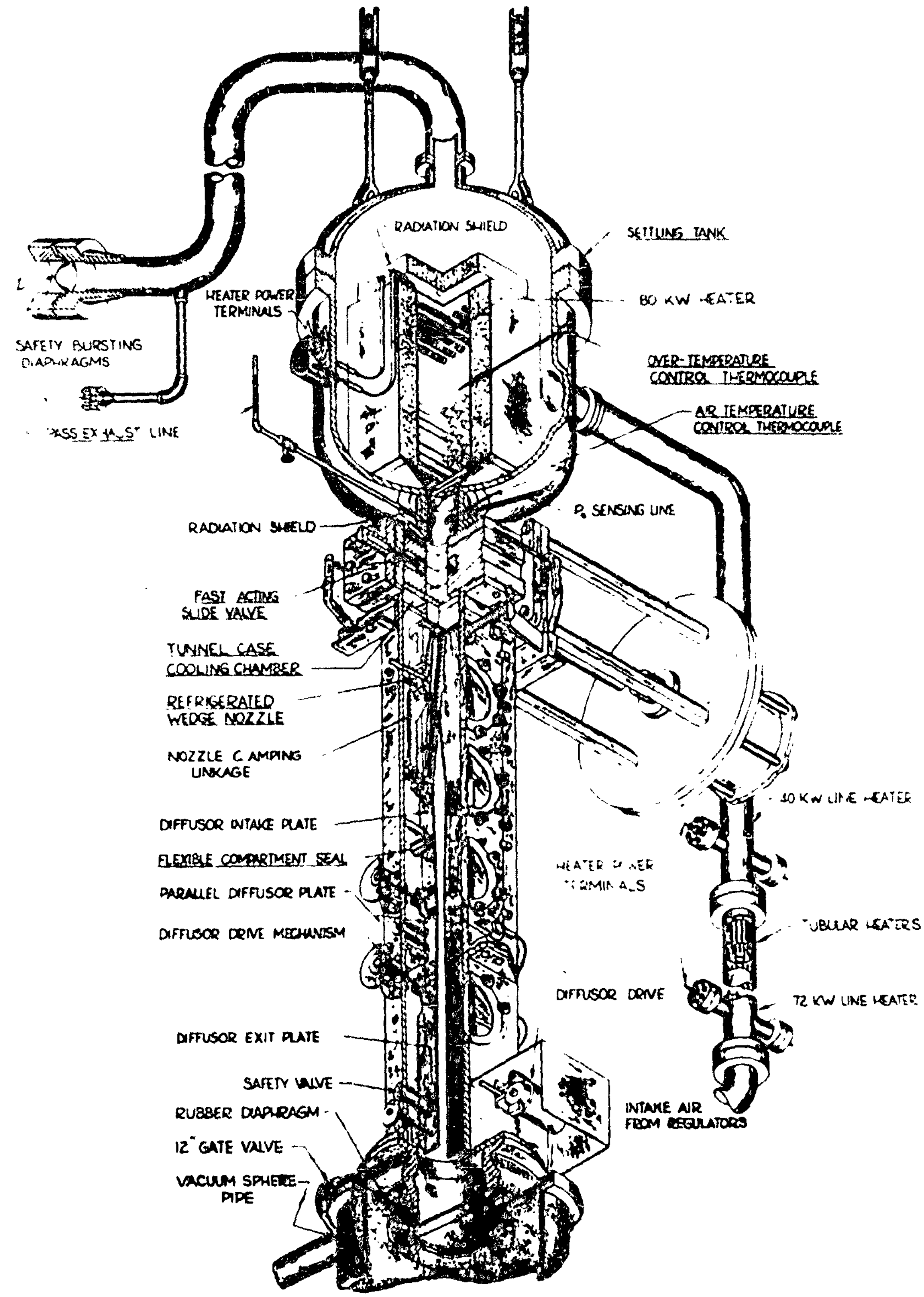


FIG. 1
ISOMETRIC SECTION OF TUNNEL NO. 4

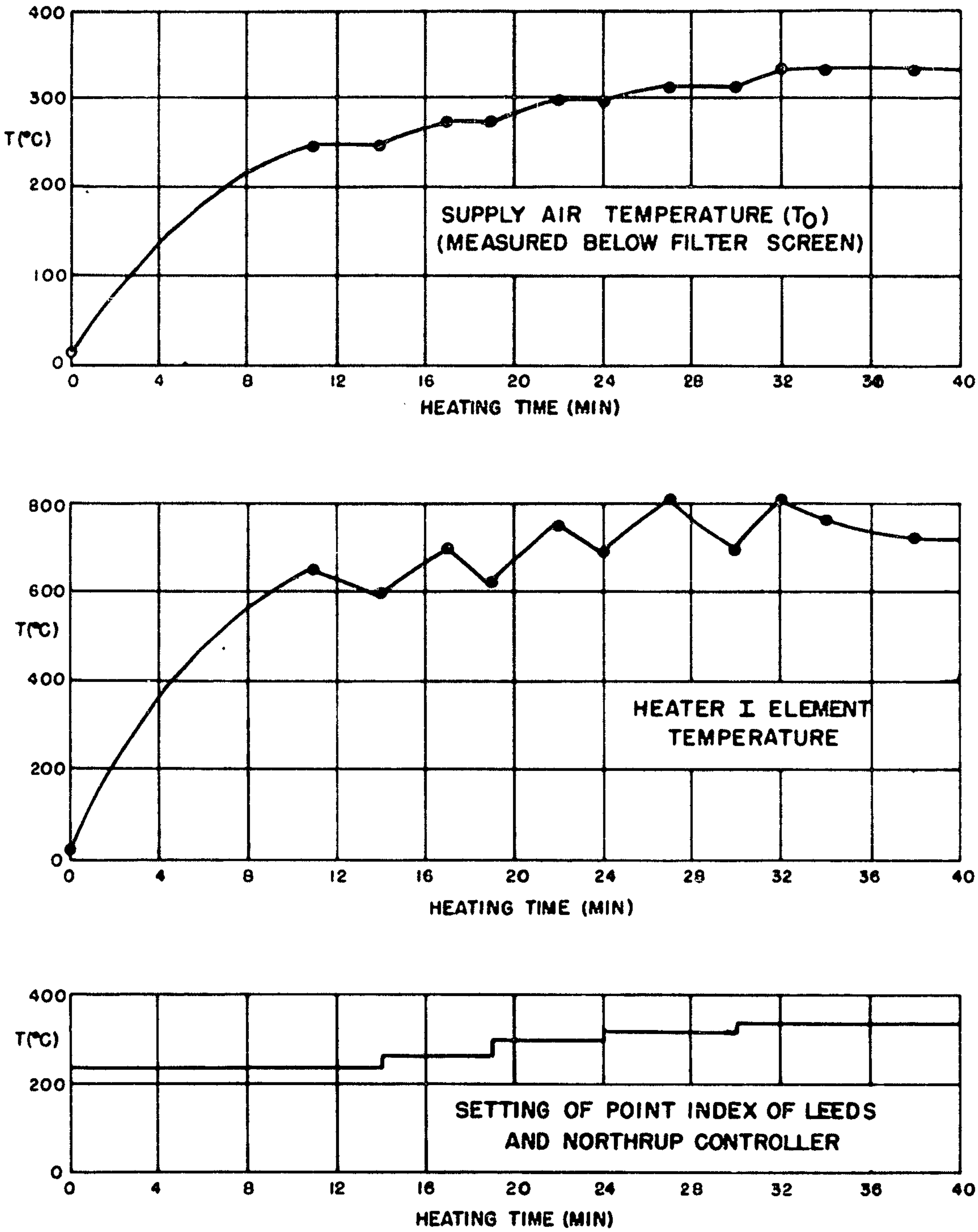


FIG. 2

TIME RECORD OF HEATING ROUTINE: HEATER I
IN OPERATION ONLY; MASS DISCHARGE AT
ROOM TEMPERATURE: .84 LB/SEC.

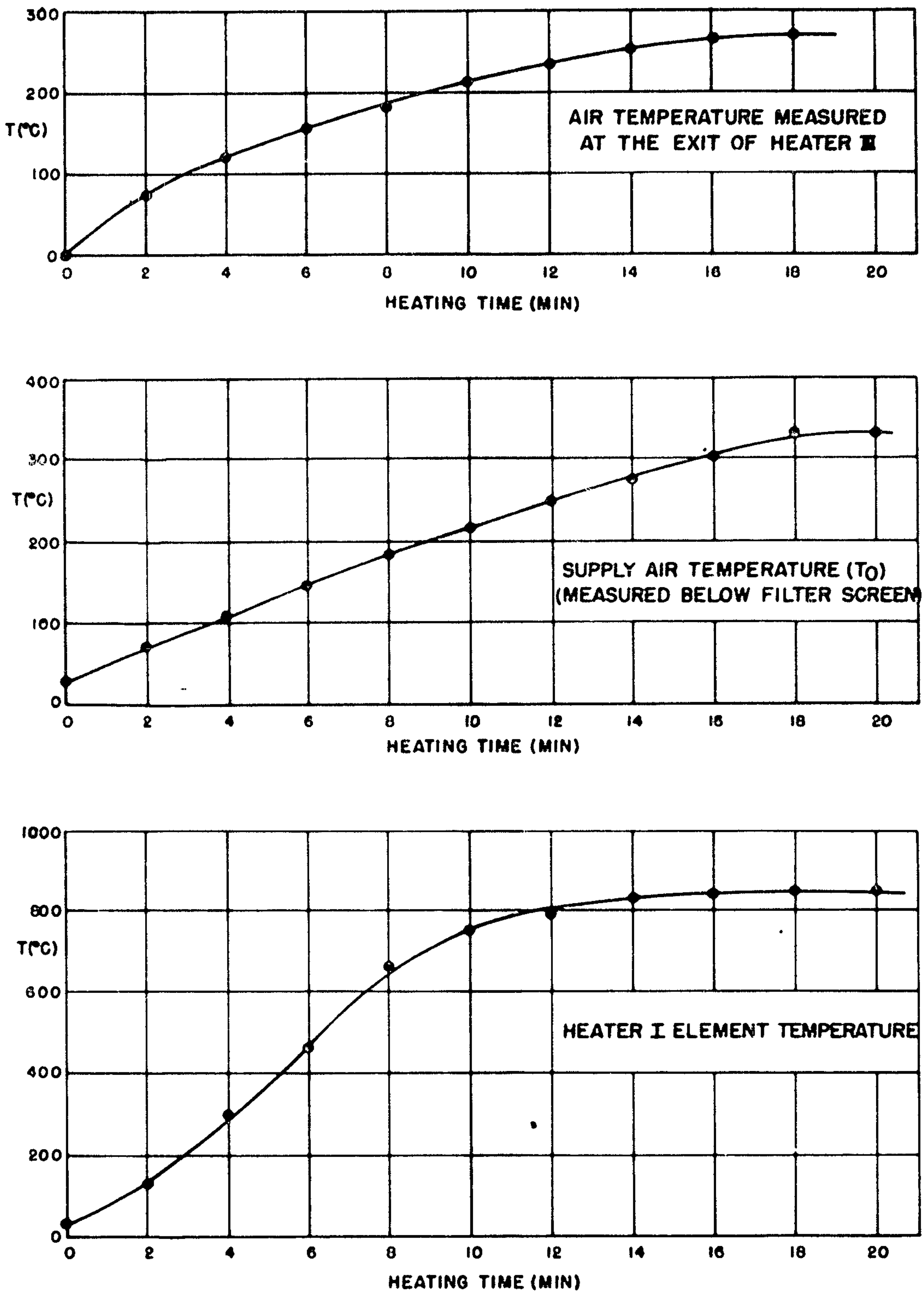


FIG. 3

TIME RECORD OF HEATING ROUTINE WITH HEATERS I AND III IN OPERATION, MASS DISCHARGE AT ROOM TEMPERATURE: .84 LB/SEC.

SCALE : 2:1

FIG. 4
SUBSONIC TOTAL TEMPERATURE PROBE

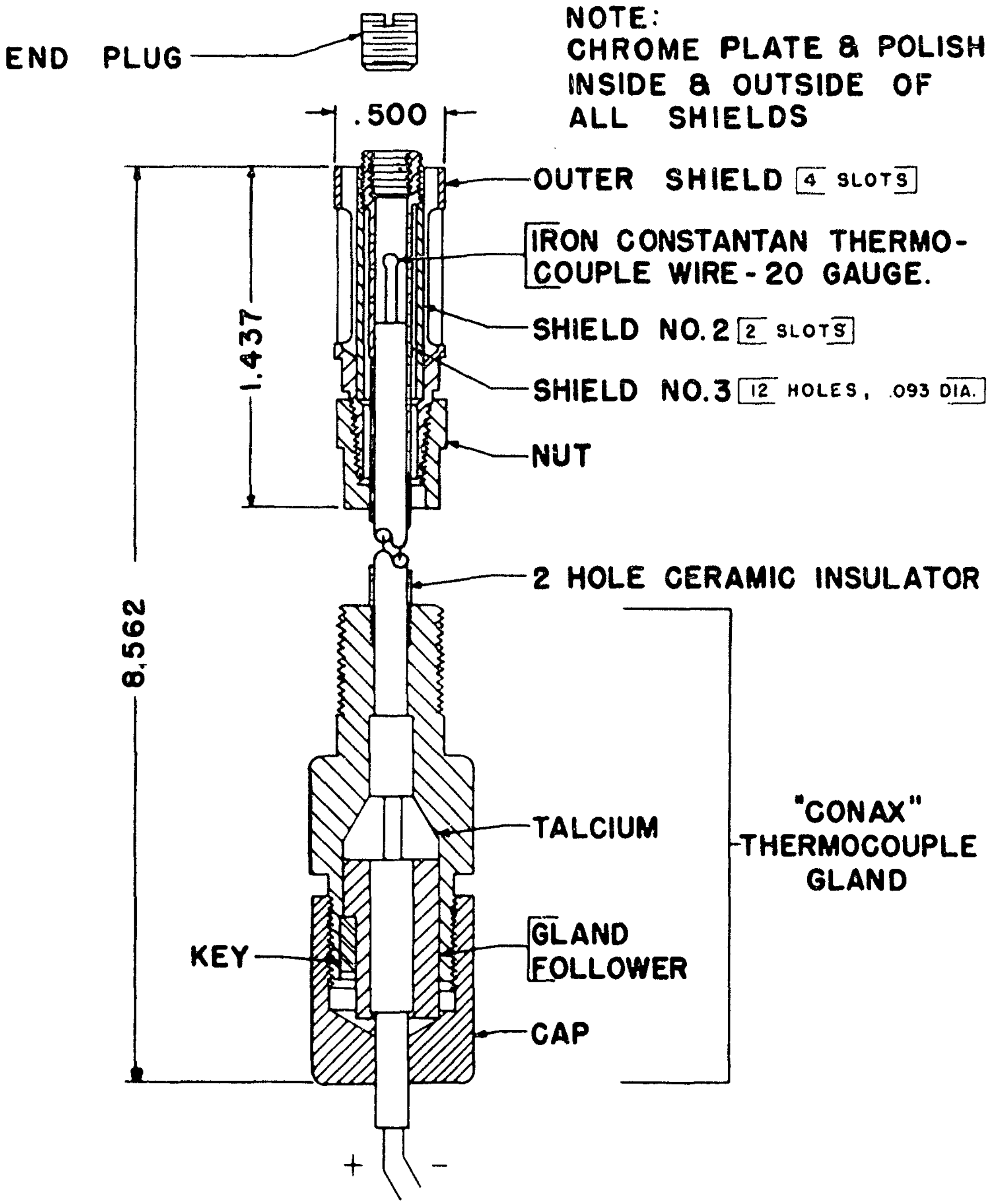


FIG. 5

MULTIPLE SHIELDED AND VENTED THERMOCOUPLE

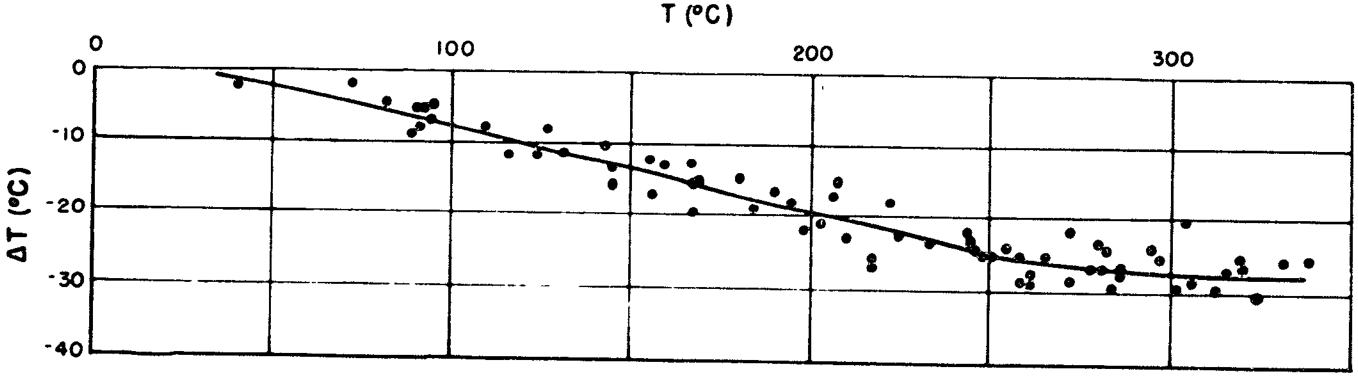


FIG. 6

COMPARISON OF BARE WIRE AND DOUBLE SHIELDED THERMOCOUPLE: ΔT ($T_{BARE\ WIRE} - T_{DOUBLE\ SHIELD}$) VS READING OF DOUBLE SHIELDED THERMOCOUPLE

MEASUREMENTS MADE IN NECK BETWEEN HEATER I AND TUNNEL INLET

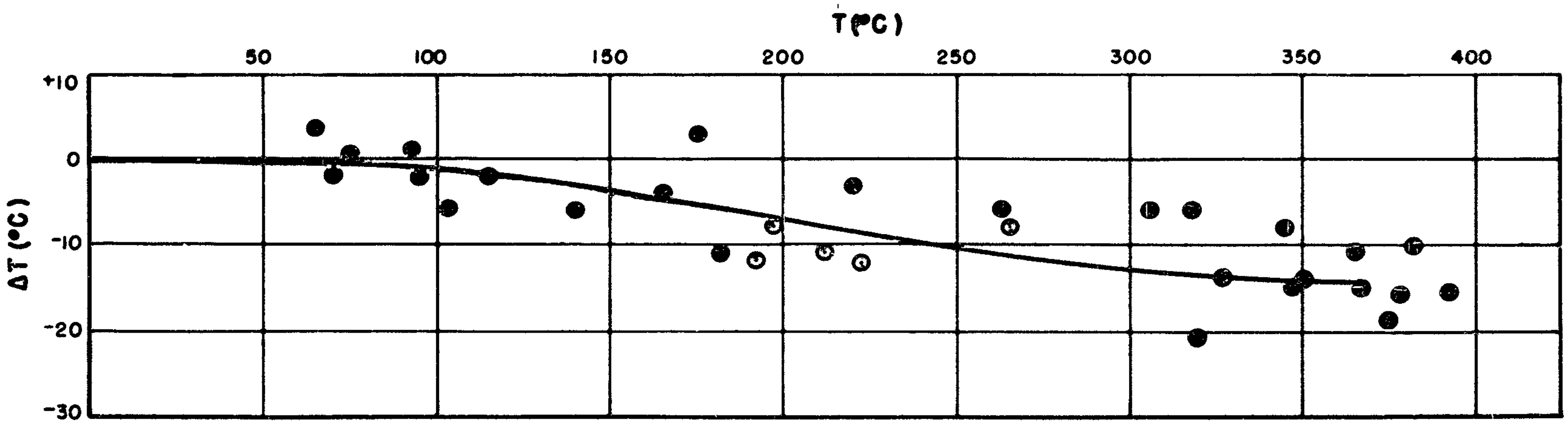


FIG. 7

COMPARISON OF SINGLE – SHIELDED AND DOUBLE SHIELDED THERMOCOUPLE: $\Delta T(T_{SINGLE\ SHIELD} - T_{DOUBLE\ SHIELD})$ VS. READING OF DOUBLE-SHIELDED THERMOCOUPLE

MEASUREMENTS MADE IN NECK BETWEEN HEATER I AND TUNNEL INLET

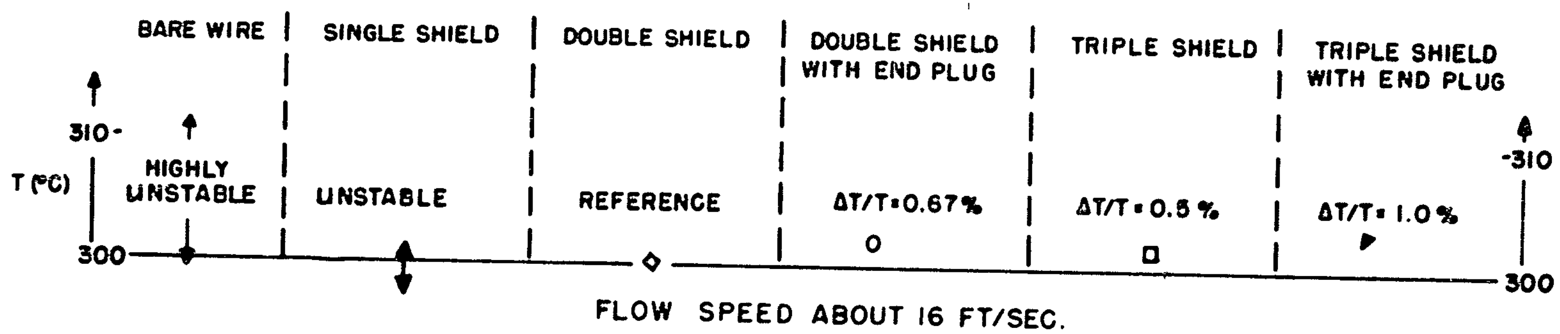
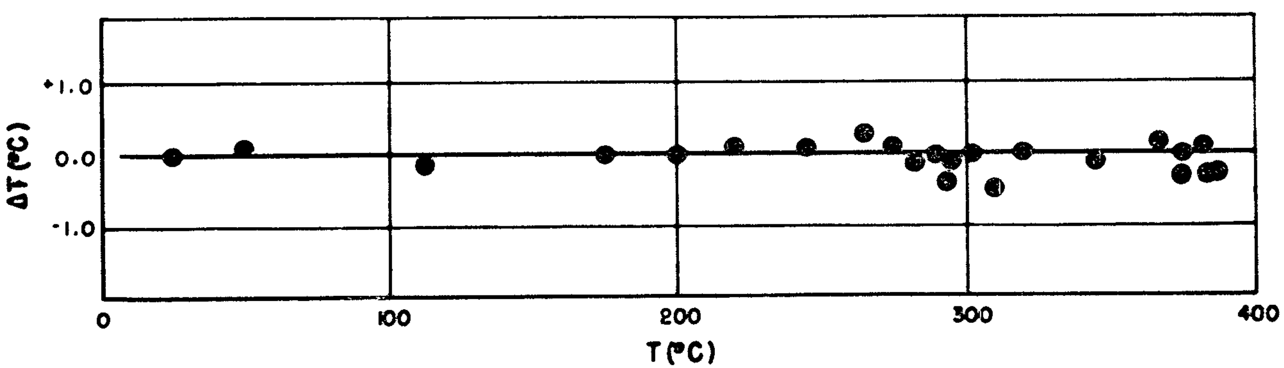


FIG. 8 COMPARISON OF BARE WIRE AND VARIOUSLY SHIELDED THERMOCOUPLES IN CROSS-FLOW AT $T_{REFERENCE} = 300°C$

MEASUREMENTS MADE IN NECK BETWEEN HEATER I AND TUNNEL INLET



$\Delta T = T_{CROSS-FLOW} - T_{PARALLEL\ FLOW}$

$(\Delta T/T)_{MAX} = .2\%$

FIG. 9

COMPARISON OF DOUBLE SHIELDED THERMOCOUPLES IN PARALLEL-AND CROSS-FLOW FOR MEASUREMENT OF T_O

MEASUREMENTS MADE IN NECK BETWEEN HEATER I AND TUNNEL INLET

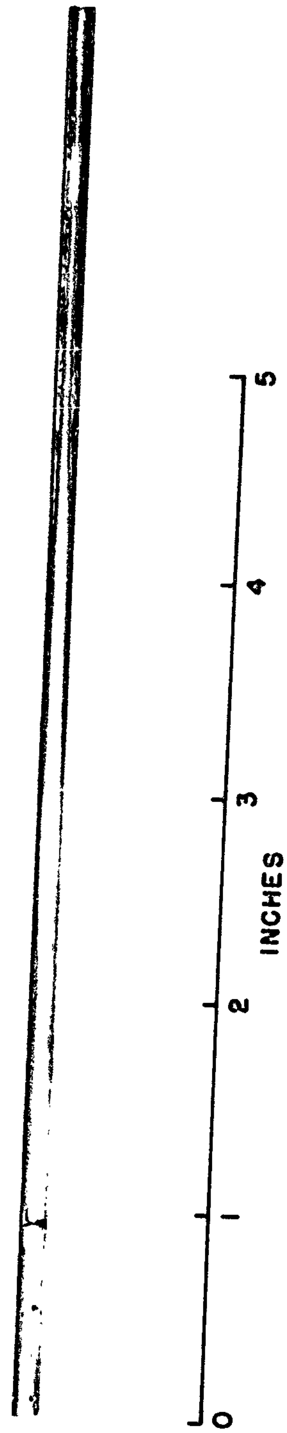


FIG. 10
SUBSONIC TOTAL TEMPERATURE PROBE

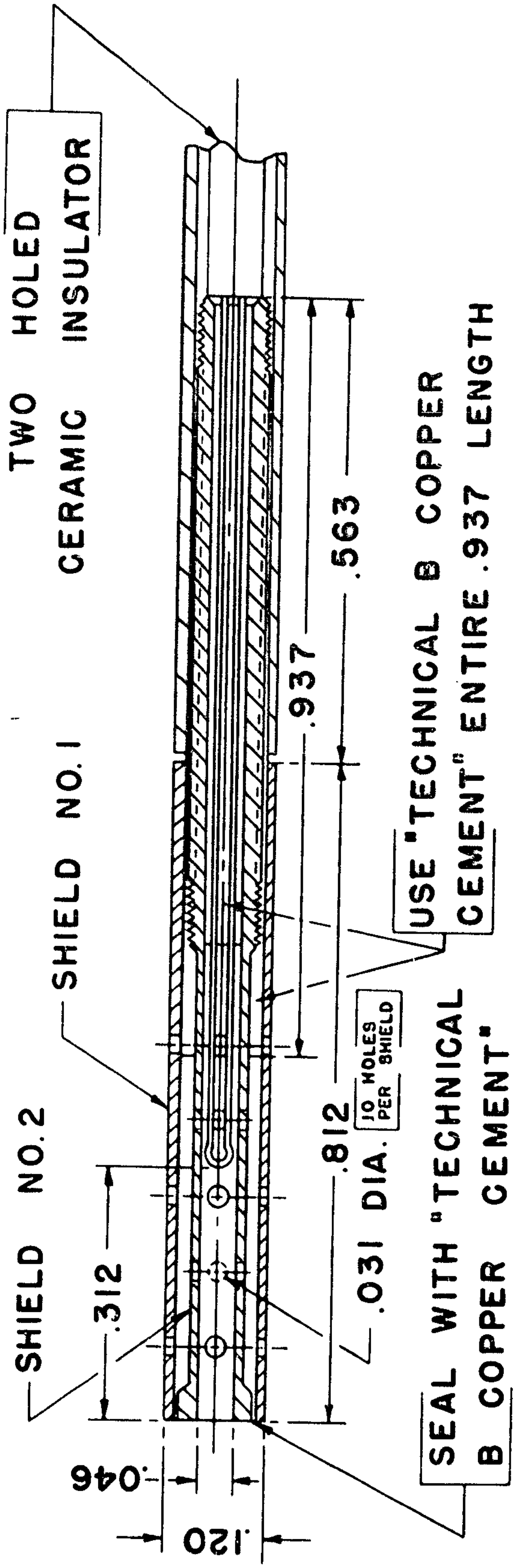


FIG. 11
HEAD OF DOUBLE SHIELDED THERMOCOUPLE FOR T_o MEASUREMENTS

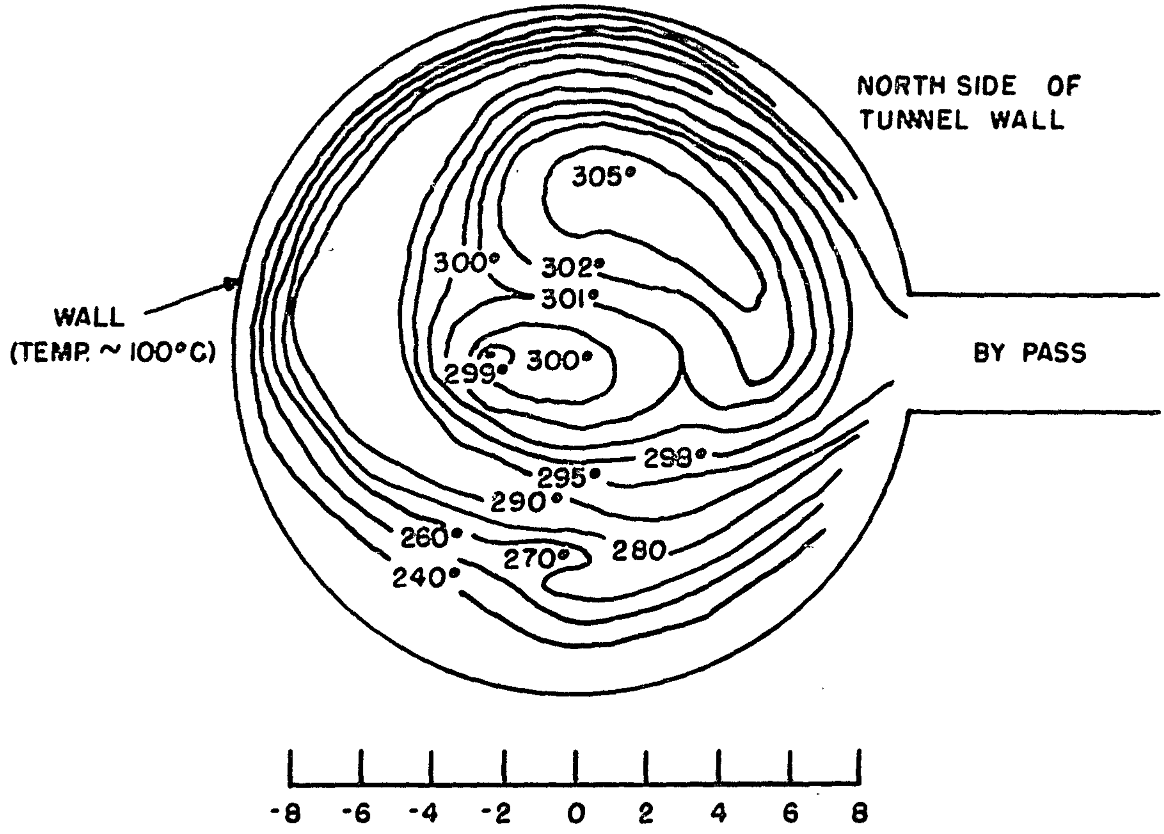


FIG. 12 TEMPERATURE DISTRIBUTION ABOVE SLIDE VALVE AT T_0= 300°C AND EXTERIOR WALL TEMPERATURE OF 100°C.

BY-PASS OPEN, P_0=10 ATM, M_S= 7.6

NOTE: ON BY-PASS SIDE T-VALUES FLUCUATE ABOUT ± 2% FROM 4CM ON TOWARDS BY-PASS OPENING.

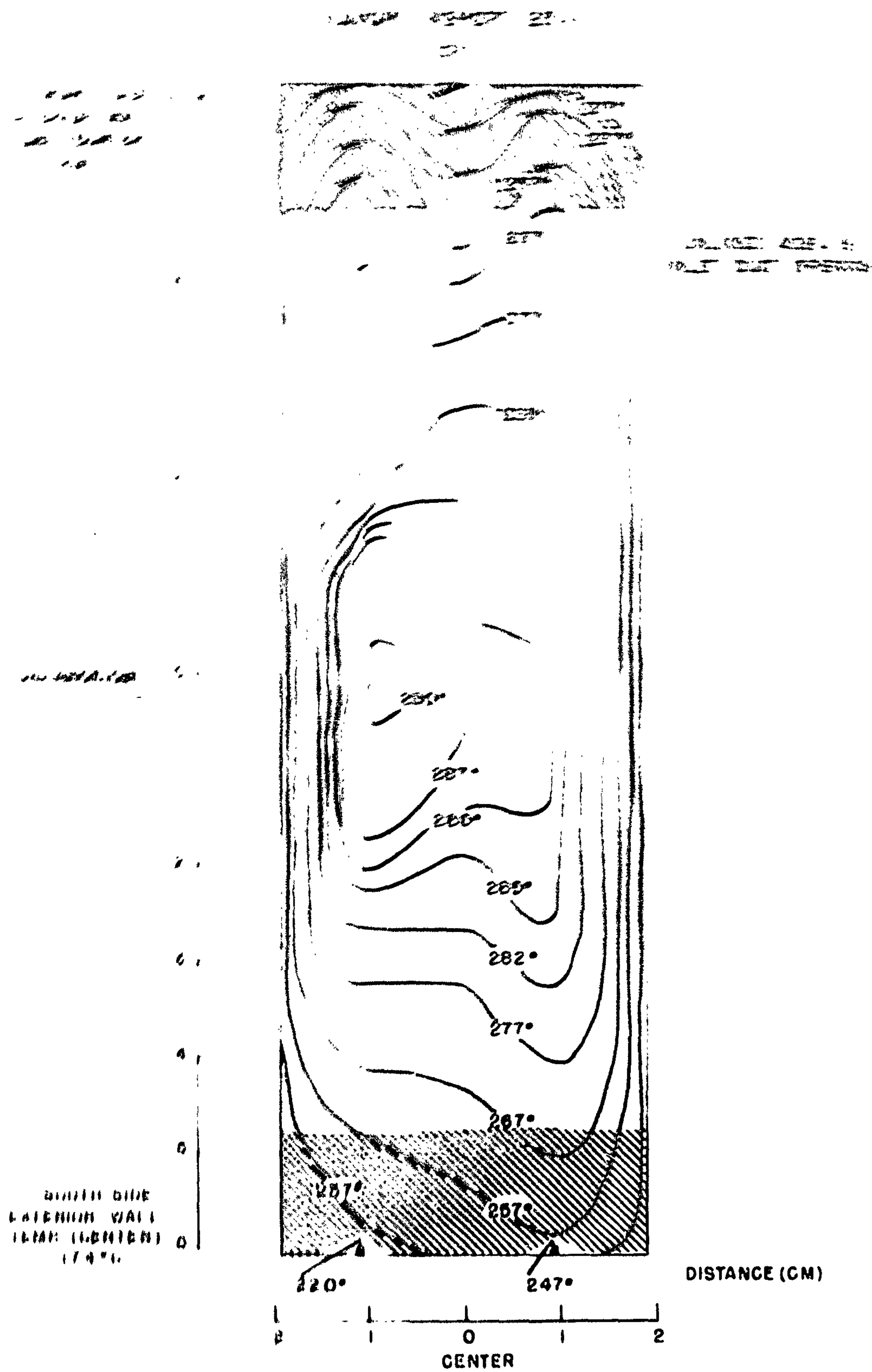


FIG 15 TEMPERATURE DISTRIBUTION .64 CM BELOW FILTER SCREEN AT 287°C; NOZZLE CASING NOT COOLED.

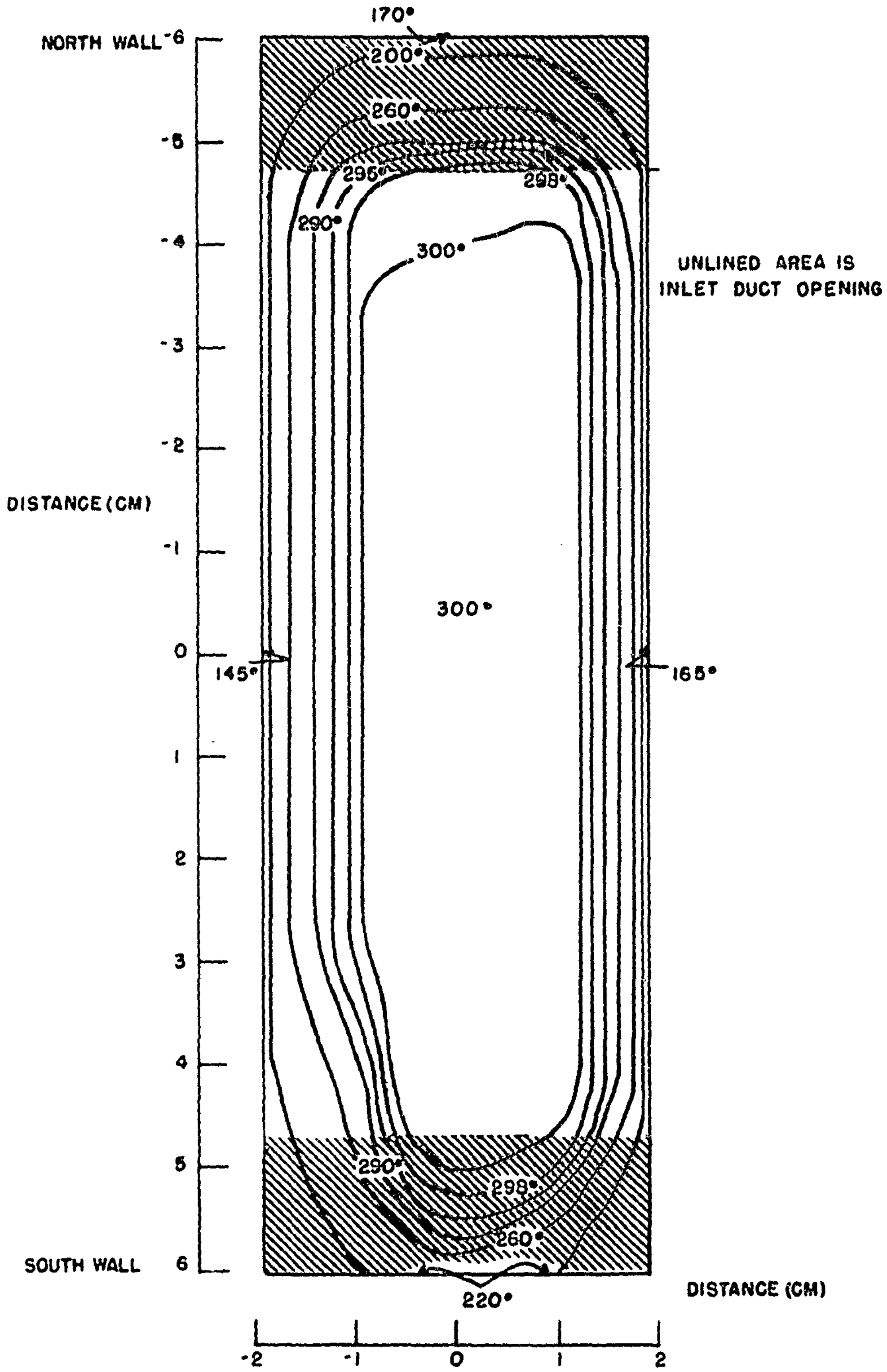


FIG. 14 TEMPERATURE DISTRIBUTION .64CM BELOW FILTER SCREEN AT 300°C, BAFFLE SYSTEM AND HONEYCOMB IN INLET DUCT; NOZZLE CASING NOT COOLED.

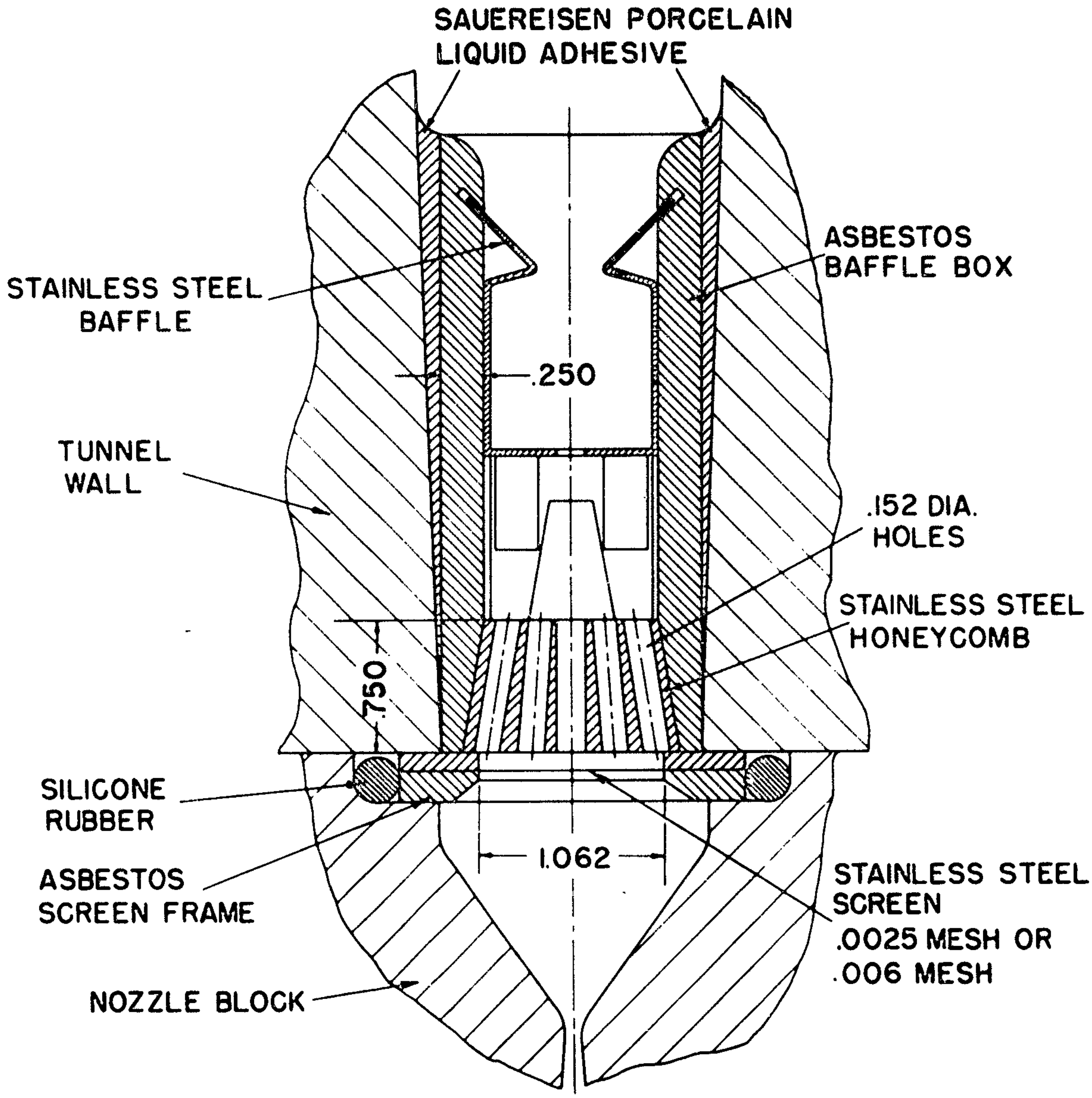


FIG. 15
DETAILS OF INLET DUCT FOR N.O.L.
HYPERSONIC TUNNEL NO. 4

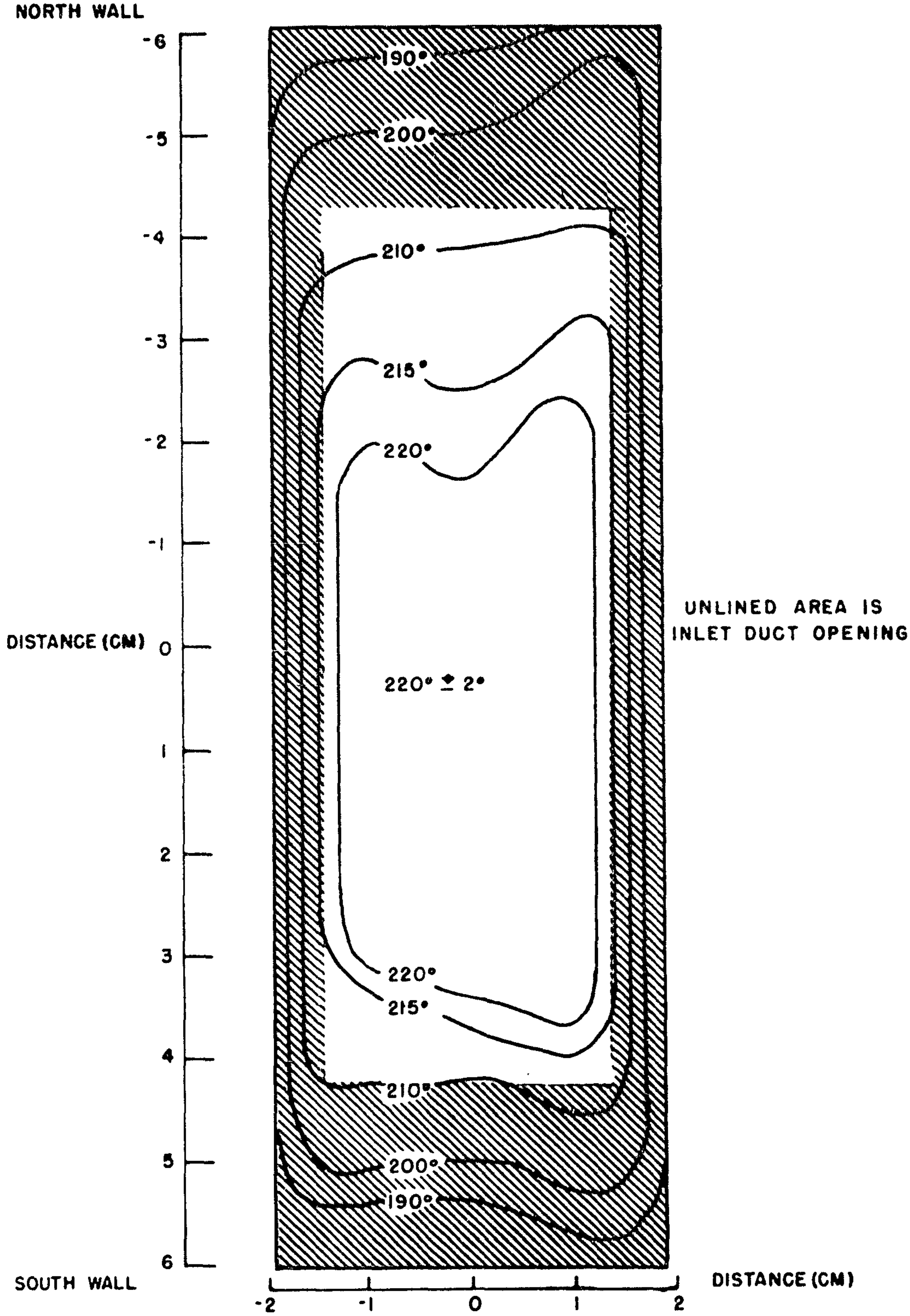


FIG. 16 TEMPERATURE DISTRIBUTION .64 CM BELOW FILTER SCREEN AT 220°C

BAFFLE SYSTEM AND HONEYCOMB IN ASBESTOS LINED INLET DUCT; NOZZLE CASING COOLED.

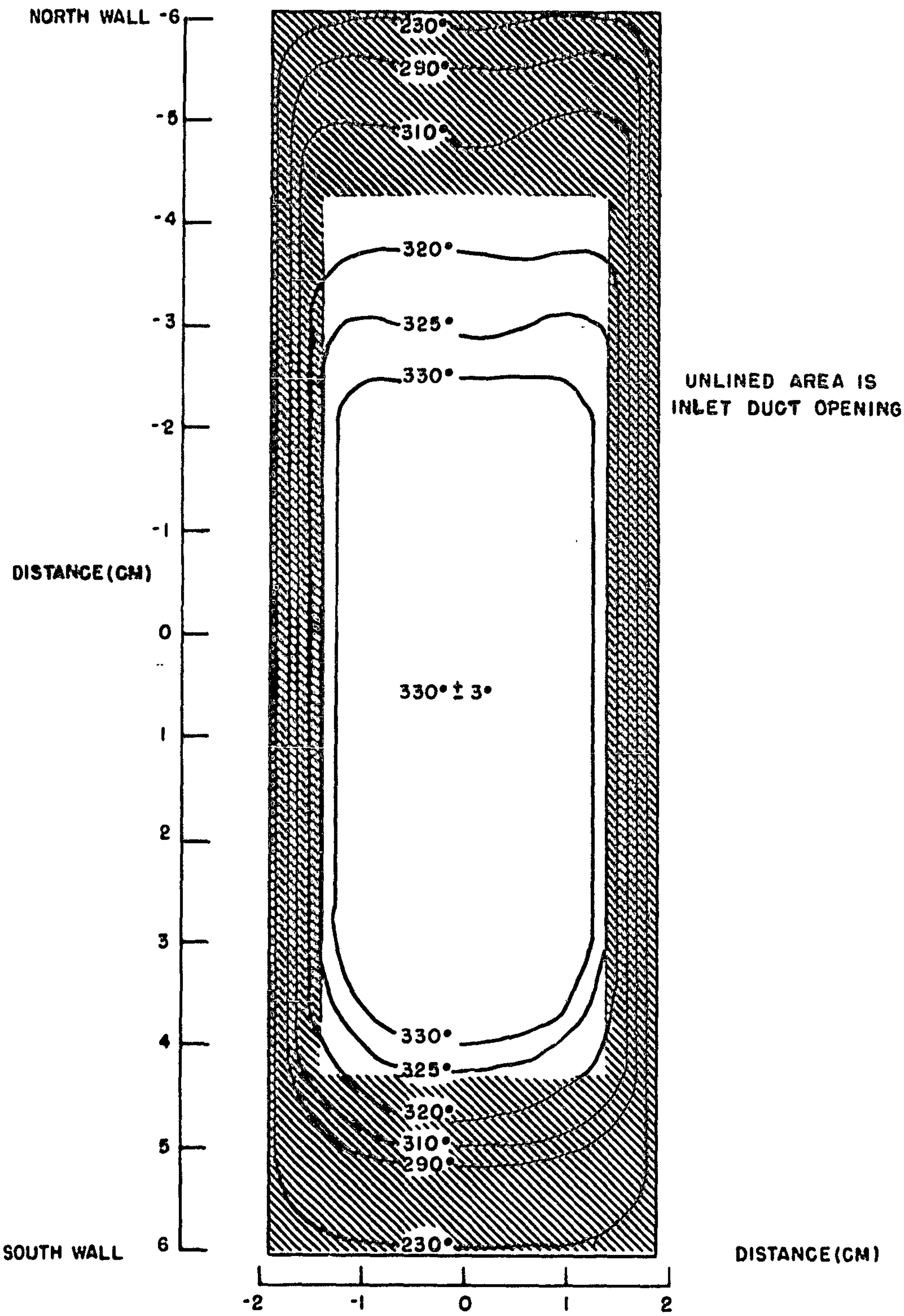


FIG. 17 TEMPERATURE DISTRIBUTION .64 CM BELOW FILTER SCREEN AT 330°C, BAFFLE SYSTEM AND HONEYCOMB IN ASBESTOS LINED INLET DUCT; NOZZLE CASING COOLED.

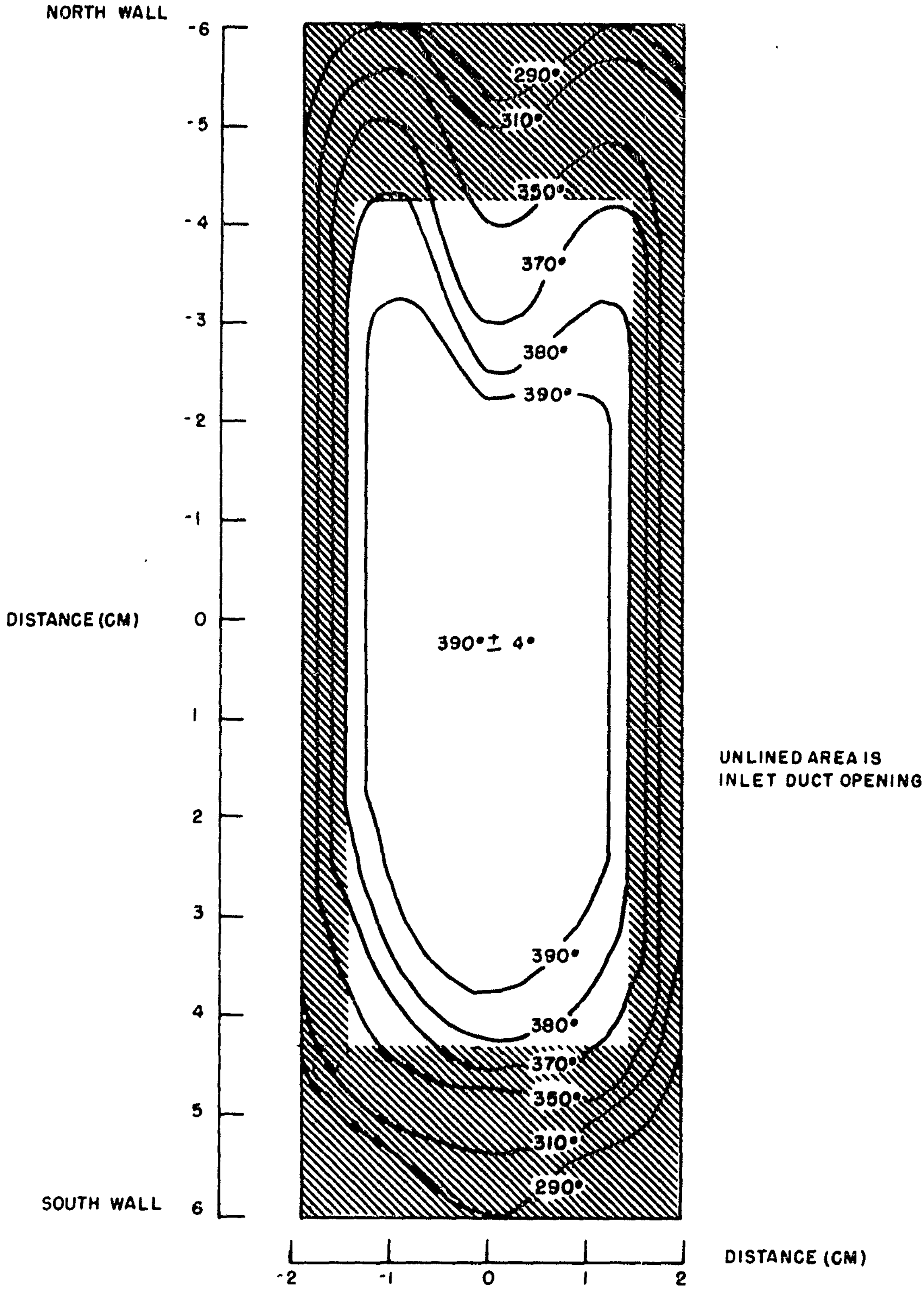


FIG. 18 TEMPERATURE DISTRIBUTION .64 CM BELOW FILTER SCREEN AT 390°C; BAFFLE SYSTEM AND HONEYCOMB IN ASBESTOS LINED INLET DUCT; NOZZLE CASING COOLED.

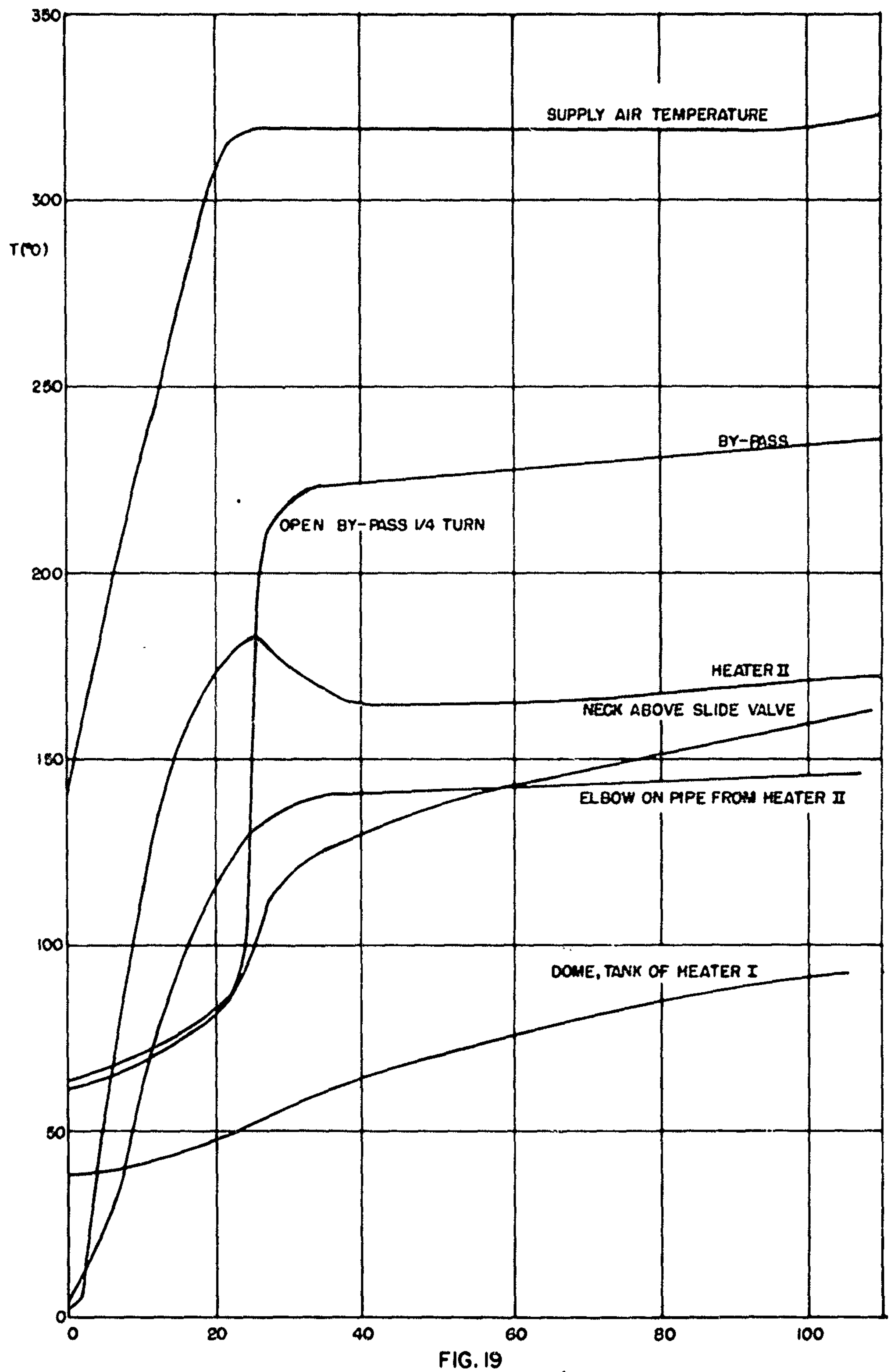
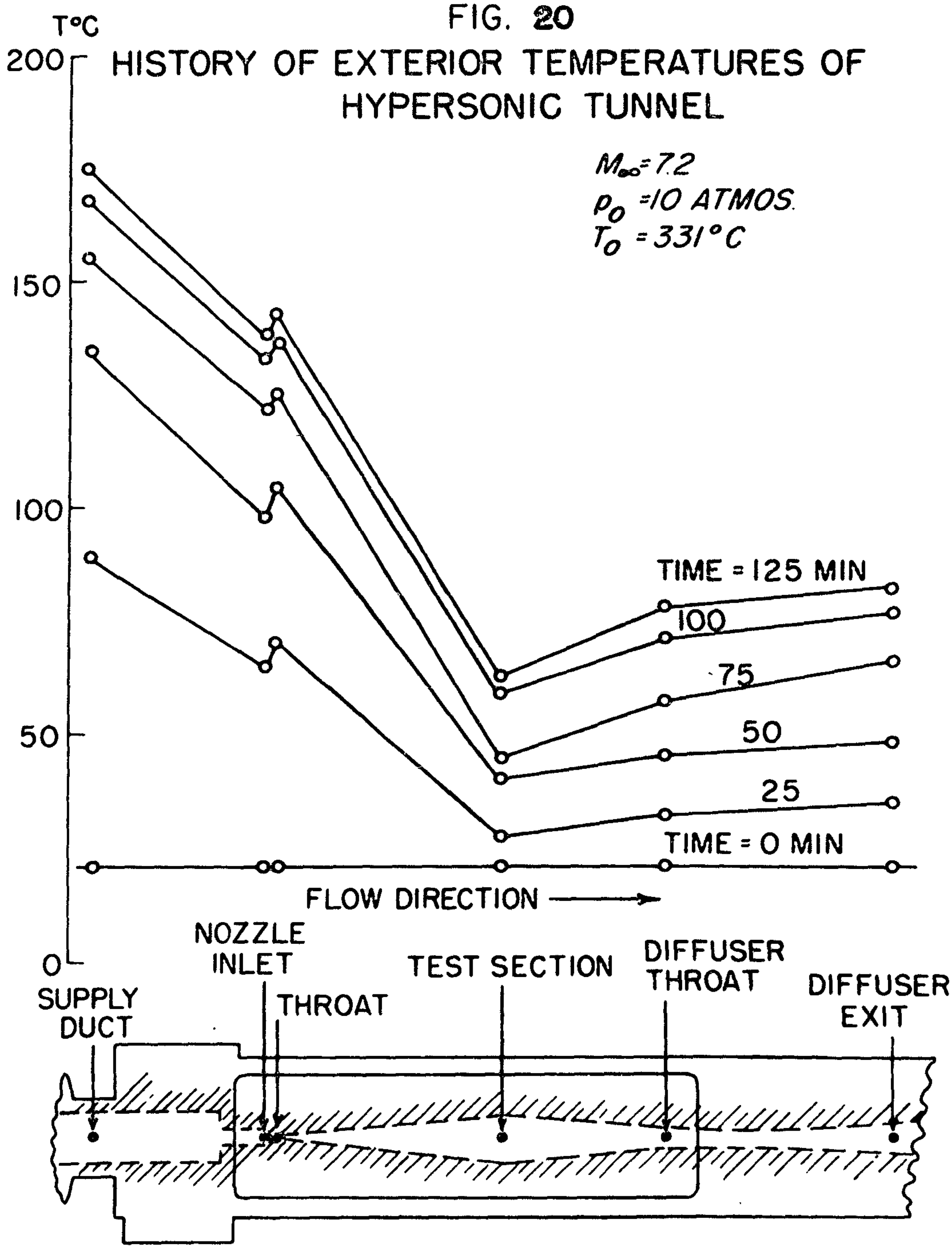


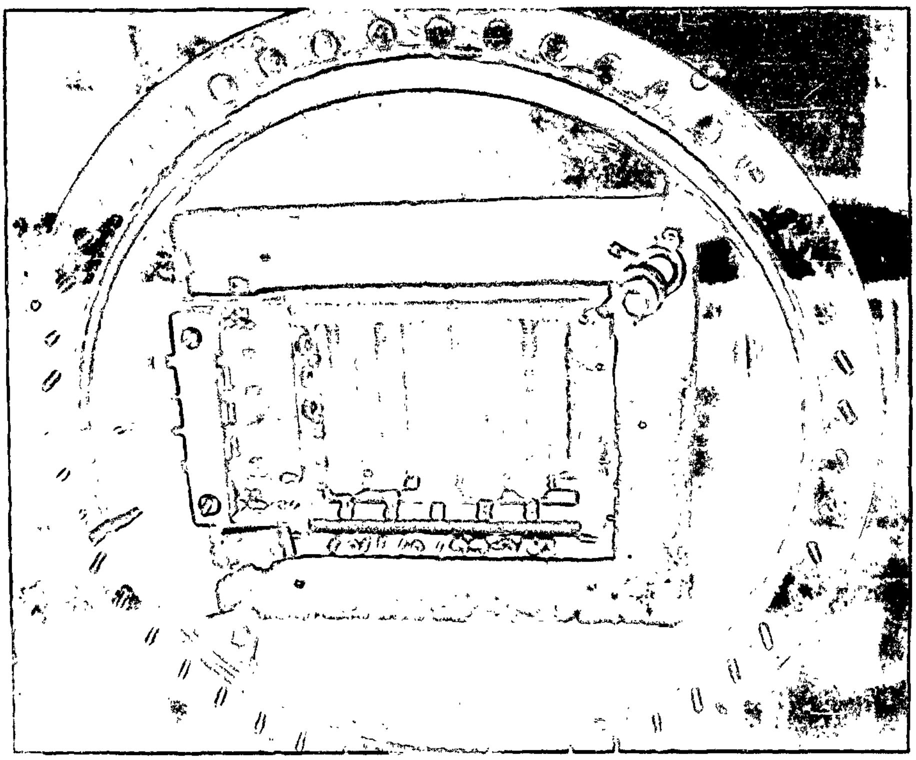
FIG. 19

HISTORY OF EXTERIOR WALL TEMPERATURES OF HYPERSONIC TUNNEL, SUPPLY AIR TEMPERATURE 318°C, MASS-DISCHARGE .84 LB/SEC AT ROOM TEMPERATURE.

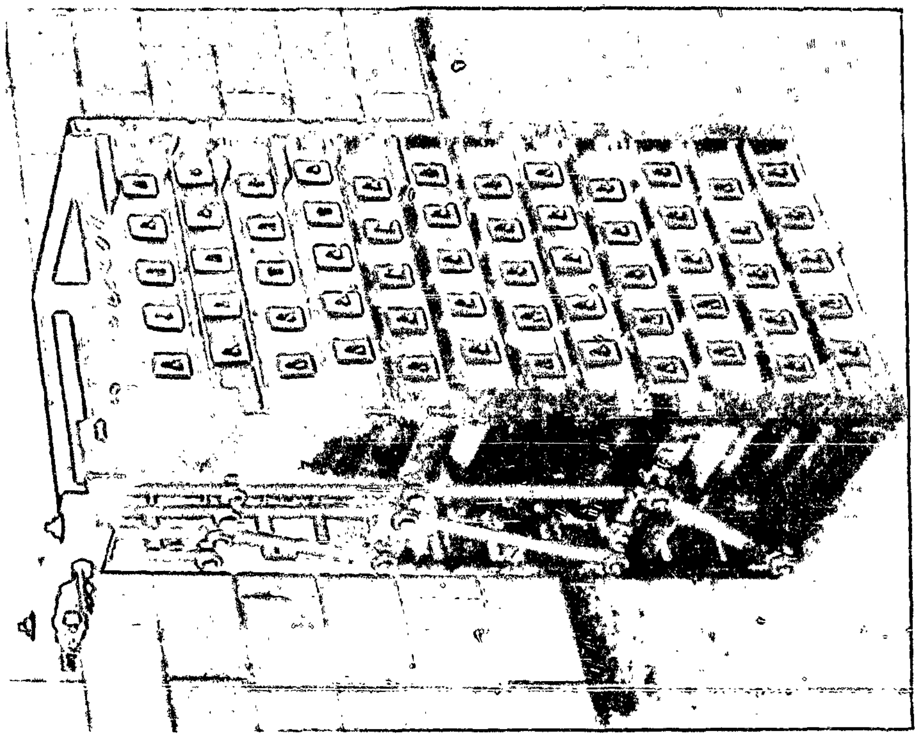
FIG. 20

HISTORY OF EXTERIOR TEMPERATURES OF HYPERSONIC TUNNEL





a. VIEW OF SETTLING TANK AND HEATER I UNIT



b. HEATER I UNIT

FIG. 21

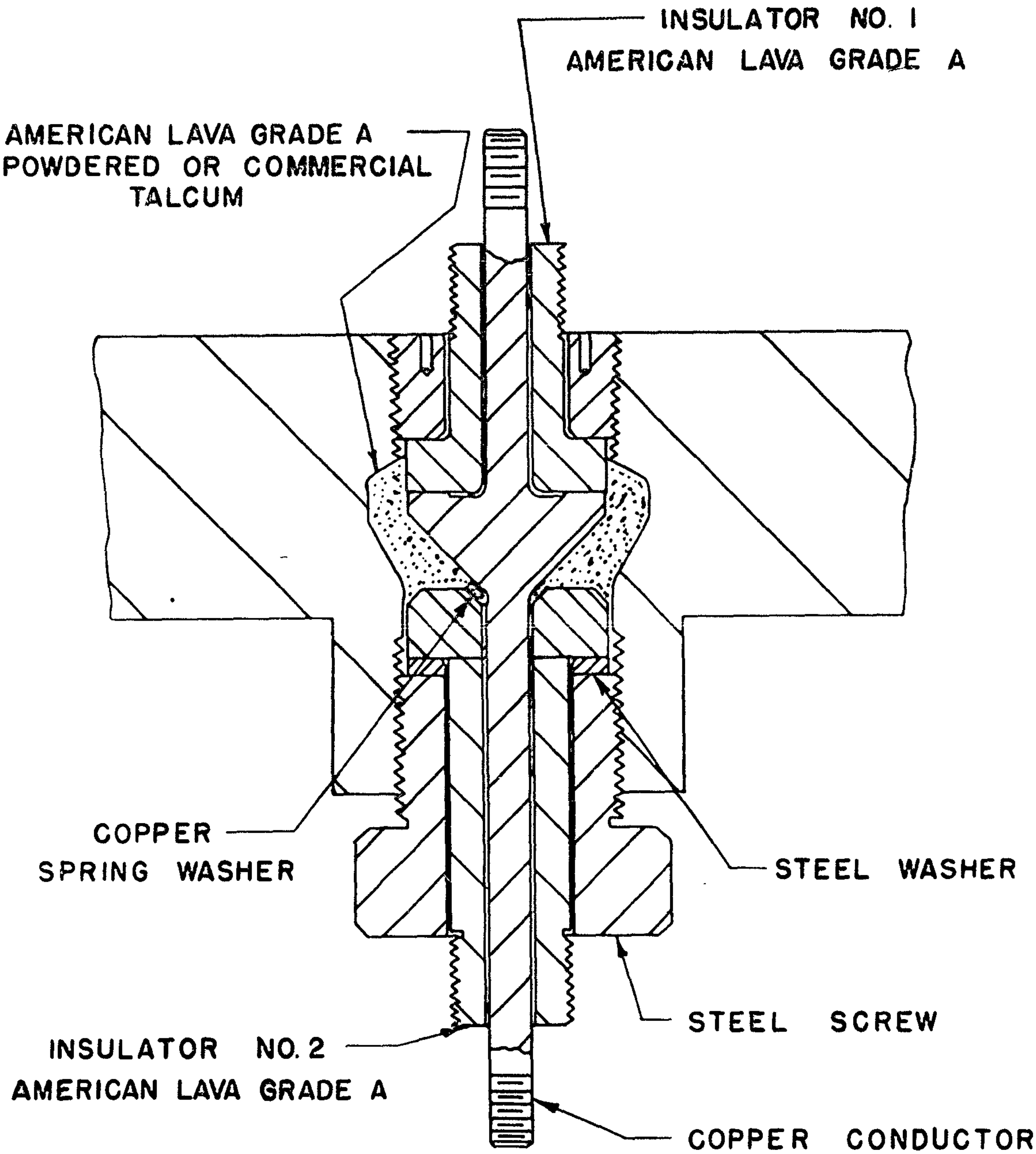


FIG. 22

HEATER POWER TERMINAL

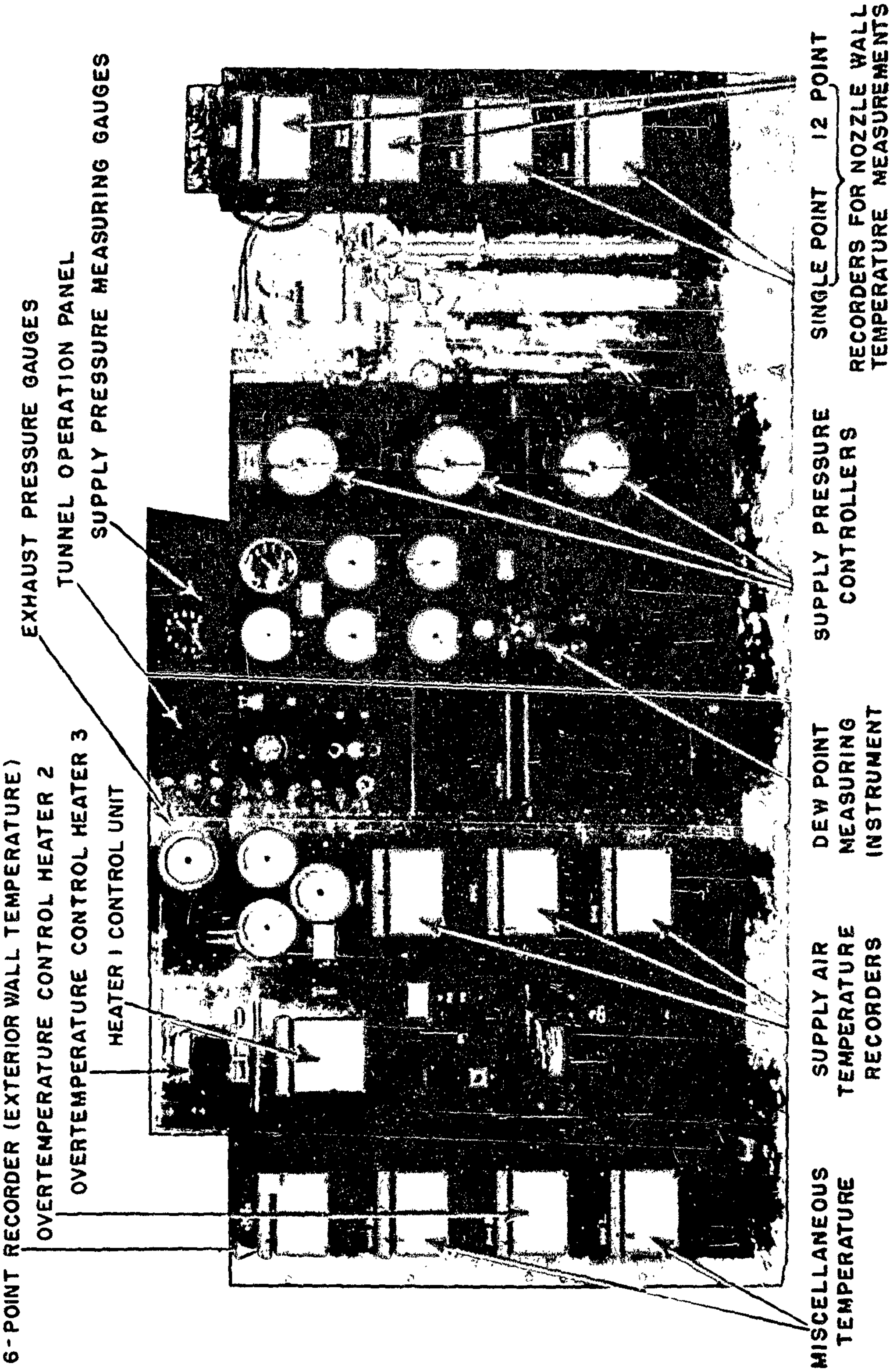
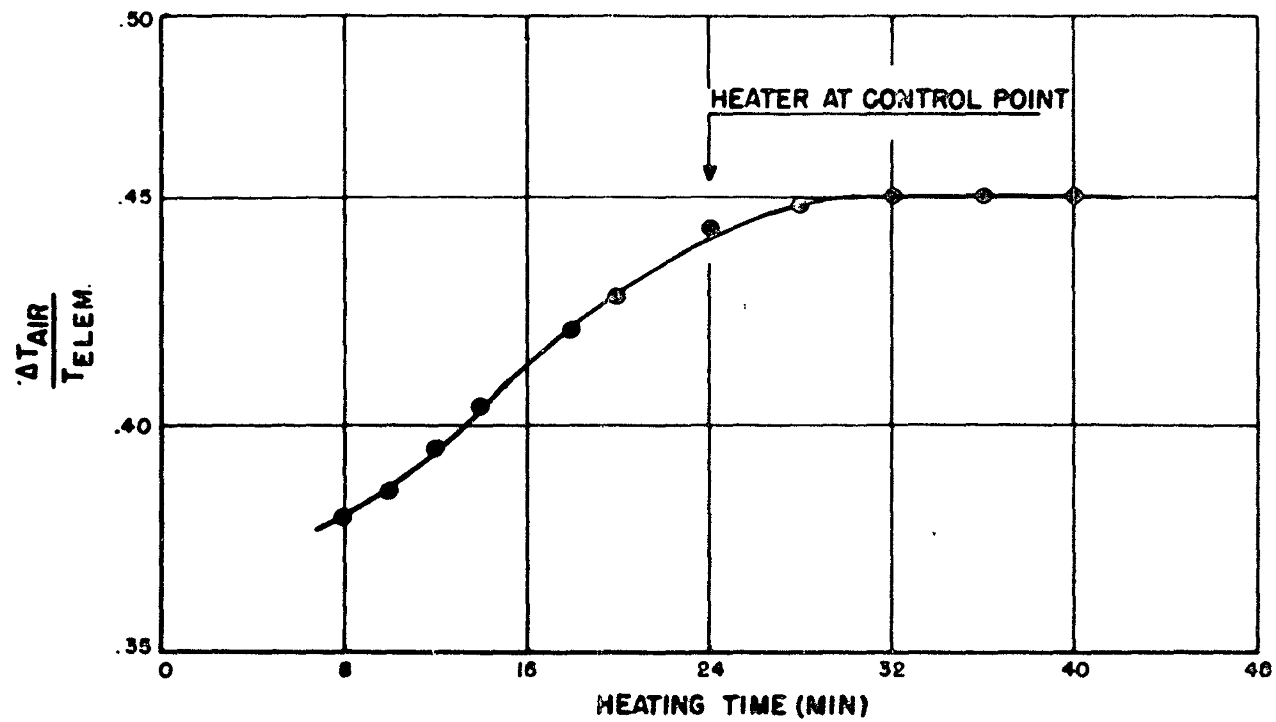


FIG. 23 CONTROL PANEL OF HYPERSONIC TUNNEL



$\Delta T_{AIR} \sim T_O$ MINUS TEMPERATURE OF INCOMING AIR, MEASURED IN DEGREE C.

$T_{ELEM.} \sim$ ELEMENT TEMPERATURE, IN DEGREE C, AS MEASURED BY OPTICAL PYROMETER.

FIG. 24

EFFICIENCY OF TEMPERATURE EXCHANGE IN HEATER I AS FUNCTION OF HEATING TIME FOR A MASS DISCHARGE OF .84 LB/SEC AT ROOM TEMPERATURE AND A DEMANDED T_O OF 330 °C

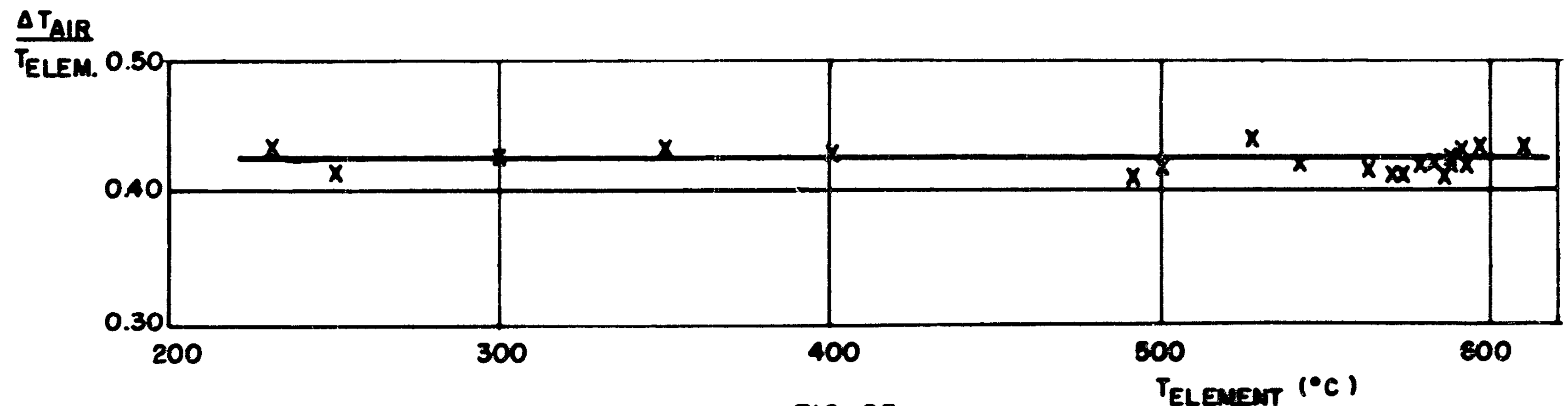


FIG. 25

EFFICIENCY OF TEMPERATURE EXHANGE IN HEATER II AFTER 1 HOUR OF PREHEATING; SUPPLY PRESSURE 10 ATM, MASS DISCHARGE .84 LB/SEC AT ROOM TEMPERATURE

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